p. 5

LUNAR ARTICULATED REMOTE TRANSPORTATION SYSTEM

FLORIDA A&M UNIVERSITY/FLORIDA STATE UNIVERSITY

N91-18130

The students of the FAMU/FSU College of Engineering continued their design from 1988-1989 on a first generation lunar transportation vehicle for use on the surface of the Moon between the years 2010 and 2020. Attention is focused on specific design details on all components of the Lunar Articulated Remote Transportation System (Lunar ARTS). The Lunar ARTS will be a three-cart, six-wheeled articulated vehicle. Its purpose will be the transportation of astronauts and/or materials for excavation purposes at a short distance from the base (37.5 km). The power system includes fuel cells for both the primary system and the back-up system. The vehicle has the option of being operated in a manned or unmanned mode. The unmanned mode includes stereo imaging with signal processing for navigation. For manned missions the display console is a digital readout displayed on the inside of the astronaut's helmet. A microprocessor is also on board the vehicle. Other components of the vehicle include a double wishbone/flexible hemispherical wheel suspension; chassis; a steering system; motors; seat restraints; heat rejection systems; solar flare protection; dust protection; and meteoroid protection. A one-quarter scale dynamic model has been built to study the dynamic behavior of the vehicle. The dynamic model closely captures the mechanical and electrical details of the total design.

OVERVIEW

It is inevitable that humans will venture beyond the Earth's boundaries and into space. Permanent habitation of the Moon is the first step towards future exploration. First-generation exploration (year 2010-2020) will include a base inhabited by approximately 15 astronauts (scientists, engineers, and doctors) whose purpose will be to explore the lunar surface and begin the building of permanent bases for lunar colony habitation. It will be necessary for the astronauts to have a reliable transportation system during their lunar stay whose operation is independent on the time of day it is being used (except in the case of solar-flare activity). This transportation system must be able to provide adequate transportation for two astronauts for a maximum excursion time of 10 hours. There must also be the capability of carrying additional payload such as additional people or large amounts of lunar regolith. The Lunar Articulated Remote Transportation System (Lunar ARTS or LARTS) is designed for this purpose.

This vehicle consists of three carts. The first cart carries the astronauts, the navigation equipment, the cameras, directional lighting and backup communication system hardware. The second cart houses the power system, the solar-flare protection blanket, and the heat rejection system for the power system. The third cart will be used for carrying cargo or for two additional astronauts. The vehicle will also have the capability of being operated in an unmanned mode. Using the concept of articulation and detachable hitches, the vehicle will be able to operate with either two carts or three carts. The first two carts will be permanently hitched together, while the second and third cart will be joined together with a flexible, removable hitch that will allow the astronauts to detach the third cart.

DESIGN REQUIREMENTS FOR THE LUNAR ARTS

The design constraints for the Lunar ARTS include operation, performance, and configuration requirements. The design requirements were set in accordance with the purpose of the Lunar ARTS vehicle, which is to transport astronauts and material on the Moon between the years 2010 and 2020.

Operation Requirements

This vehicle will be in operation between the years 2010 and 2020. Design criteria for the vehicle include (1) reliability and simplicity; (2) maximum payload capacity of 750 kg; (3) ease of operation; (4) maintainability; and (5) mobility.

The vehicle is assumed to operate in recent lunar sites of interest characterized by data from previous landings. Two of the four sites lie on flat mare surfaces surrounded by mountains (Lacus Veris and Taurus Littrow), one lies purely in flat mare (Nubium), and one is a rugged highlands region (South Pole).

Performance Requirements

1. The vehicle will perform missions of 60 km (30 km radius from base) with passengers and 75.0 km (37.5 km radius from base) without passengers per day. There is a maximum of 10 hours per mission, which includes extra vehicular activity (EVA) time. The vehicle will travel with speeds up to 10 km/hr on a 0° slope.
2. The maximum slope angle is 30° while fully loaded.
3. The vehicle will provide controllable forward (0-10 km/hr) and reverse continuously variable speed.
4. The vehicle will provide a maximum steering turn radius of 30°.
5. There will be at least three displays that show total distance traveled for a mission, total mileage of the vehicle, and a variable-control travel display able to reset the display of distance traveled to zero. There will also be time displays that include total mission time, and a variable time with the capability of being reset to zero.
6. There will be three-dimensional vision capability for the navigation system. Two dimensions will be incorporated by stereo vision and the third dimension will use a laser range finder.

7. Protection must be provided to the astronauts for (a) dust accumulation, (b) solar reflection off Lunar ARTS surfaces, and (c) solar flare protection.

8. Design of the Lunar ARTS shall include the following safety features: (a) no sharp protuberances; (b) a restraint system to prevent astronauts from being ejected from the vehicle; (c) provision of adequate handholds for ride stability; (d) comfort; (e) no hot electrical components should be in contact with the astronauts; and (f) back-up system will be used so that no single failure of a component will endanger crew or will cause an inoperable vehicle.

9. When Lunar ARTS is brought back to lunar base, the dust will be removed.

10. The vehicle will provide materials for drilling and storage.

Configuration Requirements

1. Each wheel will have the following characteristics: elastic, solid wheels; rigid or semirigid chassis.
2. Maximum mass: 2700 kg loaded; 1480 kg unloaded.
3. Minimize operation impedance due to dust.
4. Structural system factor of safety is 1.5.
5. Provide storage space, protection, and means of attaching the Lunar ARTS tools for lunar operation.
6. House and protect cable and wiring.
7. Each wheel will must have a separate driving motor.
8. Provide display and control console.
9. Structure should be optimized for lowest weight.
10. Provide accommodations for two astronauts with EVA suits and a payload of 750 kg. Payload can include either lunar regolith or two additional astronauts with EVA suits.
11. The power source will be no more than 25% of the vehicle weight. This includes a back-up power system for locomotion and communication, as well as the heat rejection systems for the vehicle.
12. Astronauts traveling on the vehicle will have a switch on the vehicle to override automated control of vehicle.
13. Provide thermal and micrometeoroid protection.
14. Provide device to remove lunar dust and debris from Lunar ARTS while away from base.
15. Provide shock absorbers.
16. The chassis of each cart shall not exceed the overall dimensions of a length of 2.73 m (9 ft), a width of 1.83 m (6 ft) and a depth of 1.37 m (4.5 ft).

POWER

The first analysis to be performed on the vehicle is the power system. This is extremely important, as all other systems designs are dependent upon the power system. In deciding on a power system for the Lunar ARTS, it was necessary to calculate the power that was required for locomotion as well as the other components on the vehicle. This was done using two programs. The first was written to calculate the amount of power needed for locomotion when the vehicle is operating fully loaded. Wheel condition had to be specified in order to calculate the locomotion energy of the vehicle. The value obtained for locomotion was then entered into the power program in conjunction with all other components' power requirements to obtain a total power requirement for the vehicle.

Fuel Cells

When a total power requirement was obtained it was necessary to decide on what power system to use. Batteries were ruled out as a power system. Fuel cells were chosen as the means for propulsion for the Lunar ARTS vehicle. Fuel cells are a technology that has already been proven successful in many space applications. NASA experts expect to have a lunar base established by the year 2005 that will use regenerative fuel cells and photovoltaics to serve as the primary power source for the base. This system can provide a continuous supply of hydrogen and oxygen for the Lunar ARTS.

Fuel cells are classified according to type of electrolyte, type of electrode, type of fuel, temperature, and type of catalyst.

The reactants that are used in the fuel cell stacks are hydrogen and oxygen with the by-products being heat and water. The reactants can be stored either as pressurized gases or as cryogenic liquids. Storing the reactants as cryogenic liquids reduces the size, weight, and meteoroid vulnerability of the storage tanks. Reactants will be stored as cryogenic liquids and will be heated upon leaving their storage tanks to be vaporized prior to entering the fuel cell stacks (the hydrogen and oxygen must enter the stacks as a gas for operation of the vehicle). After being cooled the water is stored as a liquid.

MOBILITY

Mobility of the Lunar ARTS incorporates five sections: suspension system, wheel design, hitch design, chassis design and modeling, and center of mass. The design and analysis of each was performed by independent groups, with system integration incorporated throughout the design process. This was accomplished by having all design personnel working on the mobility section meet weekly to discuss integration issues of the mobility components.

Suspension System

The suspension system is composed of three major components: flexible hemispherical wheels, a four-bar double-wishbone linkage, and a compound spring shock absorber. The double-wishbone linkage limits the spindle assembly to vertical motion, thus keeping the tracking of the wheels in contact with the lunar surface. The compound spring in the shock absorber is coupled with flexible hemispherical wheels, and the system was modeled in DADS to determine the damping constant.

The spindle assembly at the end of the control arms holds the driving and steering motors as well as the gearing and linkages used to transmit the power effectively. The primary steering is accomplished by electronic servomotors that rotate a spindle plate. The secondary, or backup, steering is an open-loop on/off switch control operated from a power bus by means of a control stick or joystick.

Wheels

The wheels of the Lunar ARTS are a hemispherical Kevlar polymer composite shell supported on the inside by a polar array of geometrically curved ribs and protected on the outside by a Mylar cover. Of utmost importance to the wheels is their dynamic flexibility during day and night operation. The deformation of the shell as it rolls will be supported by the rib array, and protection against lunar dust buildup will come from the Mylar cover. This design offers a large ground-contact area to provide adequate traction on the lunar surface while minimizing the problem of lunar dust.

Chassis

Each of the three carts is a "shoebox" frame with wall supports and mounting beams for the suspension system. An open top was chosen instead of a closed truss design to allow an easier entry and/or loading of the mass around the center of the cart. This would reduce the task of balancing the center of mass from mission to mission. Lightweight material with radiation "shields" conducive to the needs of the heat rejection group will make up the walls of the carts.

The first cart is primarily for transportation of astronauts; navigation equipment and computers are also kept in a rear storage compartment. This is permanently fixed to the second cart, which holds the power system. The third cart is for transporting hand tools, regolith accessories, and soil samples. Because the first cart is designed to carry the astronauts, its design will vary slightly from the basic design of the second and third carts.

Spindle

The third component in the four-bar linkage is the spindle assembly. This assembly houses the servomotors and steering mechanisms, as well as serving as a mounting for the spindle plate. It is made of two parallel plates welded one on top of the other by connecting rods that keep them vertically aligned with each other. The connecting points to the control arms are therefore vertically aligned to keep a constant relative distance between the ends of the control arms and to maintain a vertical parallelogram.

A vertical plate is mounted on the outer face of the housing with its normal parallel to the x-axis. This plate, referred to as the spindle plate, has bearing blocks located at the top center and the bottom center to allow rotation in the x-z plane. Holes are drilled in the top and bottom plates to create the vertical axis, about which the spindle plate rotates. The hub of the hemispherical wheels is mounted on the spindle aligned along the x-axis.

Hitch

The degrees of freedom constitute the major constraint in the hitch design. While the rolling motion takes place between the second cart and the shaft, the pitch and yaw motions take place at the ball and socket joint on the first cart. The orientation, or line of action, of the springs must be such that the motion of the ball and socket causes pure compression of the spring. In addition, the springs must have different spring constants for two loading scenarios:

1. The vertical springs must be designed to balance moments caused by a displaced c.m. as determined by the center of mass constraints, plus a 200-Earth-pound astronaut boarding the passenger cart.
2. The side springs must not cause skidding of the carts during a turn. Note that if the first two carts are in a turn to the right, then the starboard springs will be in compression and port side springs will be in tension and vice versa, so the spring constant is one-half for each spring.

The motion of the hitch has to allow for 30° of yaw, turning, in the horizontal plane between consecutive carts. In addition, it must allow for a maximum of 25° pitch in the vertical plane and a final constraint of 45° roll between carts.

Primary Steering

The steering is accomplished by electric servomotors that rotate the spindle plate. Each wheel is turned by a separate servo that is controlled by the onboard computer. The steering servo is mounted to the housing and is connected to the spindle plate by a four-bar linkage. When the servo is actuated it will rotate the first link, which takes the rotational input, resulting in a translational output via the second link. This in turn will push or pull the third link, or spindle plate. The spindle plate will then rotate about the y-axis created by the two sealed bearings located at the top and bottom of the spindle plate.

Secondary Steering

The secondary steering or backup system is an open-loop on-off switch control operated from a power bus by means of a control stick or joystick. The power bus is wired directly from the steering servos through the joystick to the power source. It will bypass all onboard systems (i.e., onboard computers, monitoring and control devices) in case of failure. The joystick and power bus are located in the center of the forward bench seat and will allow operation from either the left or right side. Steering is accomplished by switching the power on and pushing the control stick in the desired direction of turning, left or right. Once the desired wheel angle is obtained, the stick is then returned to its center upright position.

This backup system is only effective for onboard system, wiring, or communication failures. Because this vehicle has four-wheel steering, if a steering servo fails, the vehicle can be steered by a single cart. The steering servos for the damaged or affected cart will be locked in the forward position by an auxiliary pin that secures the steering linkage to the nonrotating spindle. This will be done by a handcrank that fits into the steering servo. Once the wheels are locked, the cart with working systems will steer like a two-wheel steering vehicle. The problem of complete steering servo failure (all four wheels) was not considered because it would be highly improbable.

DISPLAY CONSOLE

On the previous lunar expeditions one of the problems that arose was the inability of the astronauts to clearly see the display information presented on the Lunar ARTS due to lunar dust. It is of the utmost importance that the astronaut be able to clearly see the display information at all times. It was, therefore, necessary to design a system to solve these problems.

In the display of information the astronaut must be able to call up various selections of data as needed for the completion of the mission goals. This could range from Lunar ARTS system information to scientific tools information status. To accomplish this task the display system must easily integrate with not only the Lunar ARTS systems but also with the numerous instruments and vehicles that could be put into use on various systems. To accomplish all the desired functions, it was decided that an inner-helmet device be used. This device consists of a fiber optics system that displays its information on a holographic medium. The display of information is accomplished in the following manner: holographic film is placed within a 30° radius of the astronaut's right eye; this film is where the information is projected. The astronaut sees the information projected at infinity, which means that the information would seem to be floating in space. When the brain sees this image it superimposes it on the image that the left eye sees; this gives the astronaut the sense that only one true image is being seen. The display system contains no high-voltage supplies and is totally fiber optic. This is preferred because there is little power drain and the astronaut is exposed to no high voltages. Since the display system is simply a means of displaying information, it may act as a display for other instrumentation as well. In the case of a helmet failure, a backup hand-held display could be plugged into the system to take the helmet display's place.

NAVIGATION AND COMMUNICATIONS

The object of the navigation system is to direct and control the movement of the Lunar ARTS from one lunar base to another, or to any point in between. In designing the system many factors concerning and relating to this purpose must be taken into consideration. Not all can be addressed here, so we will deal mostly with a description of the system and how some of these factors relate to the system.

Every control aspect of the Lunar ARTS incorporates communication systems. These systems transmit various signals including voice, data, video, and control signals. All these signals assist in the navigation of the vehicle. The following sections suggest processing and modulation schemes best suited to each of the information types. In optimizing the design, each discussion considers minimizing conversions and reducing noise effects.

The lunar environment dictates the materials of electronic equipment. Lunar radiation affects the performance of the electronic component, and for this reason, the design necessitates the use of radiation-hardened components. These components reduce the noise caused by radiation. The environmental effects of temperature also create undesirable effects in the transmission of data. Therefore, not only must the components be radiation hardened, but should be relatively temperature insensitive through a broad range of temperatures to produce predictable electronic systems. Aside from component considerations, solar effects on radio waves need be reduced. Through the use of relatively high carrier frequencies, such effects can be minimized.

The navigation system of the Lunar ARTS is required to enable the user to have remote or manual control of the vehicle. It will have the ability to determine precise distances of nearby objects for remote operations and to send three-dimensional images to a remote station, along with relevant parameters such as velocity, fuel level, and distance to target object. It also will employ a heads-up display (HUD) and interhelmet optical aid (IHOA) inside the astronaut's helmet.

Navigation

The core of the system is the central processing computer located at the lunar base. In normal operation it will coordinate and prioritize system functions. A less comprehensive back-up system will be operational on the cart. Another key element of the system is the heads-up display (HUD), a device much like the ones employed in jet fighters today. It serves as the primary link between the pilot, the Lunar ARTS, and the lunar base. A stereo vision system provides a three-dimensional image for the pilot. A computer grid map of the lunar surface, in conjunction with the relay antennas, enables precise point-to-point navigation. In designing subsystems, emphasis is placed on minimization of mass and power requirements on the Lunar ARTS, consolidation of as much hardware as possible at the lunar base, and maximum utilization of cutting-edge technology.

There are three different modes of operation: on site, remote, and programmed. The primary mode is on site. In this mode the pilot is with the Lunar ARTS on the mission, connected to and controlling the Lunar ARTS via the HUD. At any time the pilot may elect to control the Lunar ARTS manually, and be guided by the lunar base or by eyesight. The remote mode consists of the pilot using the HUD to operate the Lunar ARTS from the lunar base. The HUD provides a visual environment that is indistinguishable from on site operation. This mode is useful for missions where a human presence is not necessary, or when the on-site pilot is unable to operate the Lunar ARTS. The programmed mode consists of the central processor control operating the Lunar ARTS from software, normally without direct human intervention. It is capable of real-time adjustment to changing mission conditions. It relies on a grid map whose grid points are the locations of the communication relay antennas. A path can be learned and stored for later use. The HUD can be used in parallel to monitor the mission or for minor intervention. This mode is most often used for routine missions like resupply and raw materials transfer.

Communications

Voice and video signals sent between the cart and the base utilize the standard practices for transmitting such signals. However, the other signal types require a more specific design.

The data signals, transmitted from the cart to the base, transmit sensor values through analog FM signals. When reaching the base, a computer processes the data signals. Control signals, sent from the base to the cart, incorporate a digital FM transmission. Special byte-sized codes induce the desired changes.

Voice transmission. Although FM transmission produces clear signals, amplitude modulation (AM) produces a clarity in the transmitted signal widely acceptable for voice transmission. The AM transmitter encodes the message signal in the amplitude of the carrier signal, a standard, high-frequency sine wave. In studying the frequency response of voice signal, few frequencies are found in the near-zero range. Therefore, a single sideband (SSB) scheme for transmission is desired. In using SSB transmission, advantages include conservation of bandwidth as well as reduction in the power consumption due to the suppressed carrier.

Video transmission. Because stereo vision is incorporated in the design, two video signals need transmission. These signals, along with the data signal related to the range finder, present the required knowledge for processing the 3-D signal at the base.

Standard video transmission incorporates AM for broadcasting. The recommendation for modulation is through vestigial sideband modulation (VSB) since, unlike voice signals, video signals contain a significant amount of low-frequency information. VSB modulation includes all the data of one sideband and part of the other sideband in its transmission. Thus, the transmission insures no loss in frequencies near zero and yet uses the same bandwidth as SSB transmission. In addition, the carrier signal should be included in the transmitted signal to aid in the detection and demodulation of the signal.

HEAT REJECTION AND PROTECTION

The Lunar ARTS vehicle has to be equipped with a means of protecting the vehicle from the environment it will encounter on the Moon and a means of rejecting heat from the power system and the electrical equipment. The heat rejection system for the power system will incorporate a continuous loop of water originating in the water storage tank to reject the heat from the fuel cell stack. The water will pass from the water tank, through the stacks (to take away the by-products of water and heat), to a heat rejection system or storage system, and back to the water tank to be used again. The vehicle will be protected from meteoroid impact, solar flares, and dust accumulation. The protection and heat rejection systems depend greatly upon each other and were designed accordingly.

Worst-case scenario is taken into account for all calculations. This will occur when the sun is directly over the vehicle causing a lunar surface temperature of 230°F or 383 K. During a lunar night, the temperature of the surface is at 4 K.

Heat Rejection

Both the fuel cell system that powers the lunar rover and the electronic equipment give off heat that has to be rejected. Several different means of rejecting the heat were studied and the system that optimized the weight, amount of space, and amount of heat rejected was chosen. The system chosen to reject heat from the power system uses both active and passive cooling. This system uses a combination of a radiator and storage system during the lunar days and only a radiator during the lunar nights. Multilayer insulation blankets will be used on those components that must be kept at a constant temperature.

The heat rejection system is dependent upon the environment on the Moon. The incident radiant flux from the sun is 1360 W/m^2. The surrounding temperature is assumed to be that of deep space or -269°C (4 K). The heat rejection system must be capable of delivering 400 W of heat from the fuel cell stacks. The temperature of the water entering the heat rejection system will be 96°C or 369 K, while the temperature leaving the system is required to be 85°C or 358 K. The amount of heat that has to be removed from the electrical components is 43.2 W. The systems chosen also have to provide for both meteoroid and dust protection. It is assumed that the temperature at the lunar base will be kept at 22°C or 295 K.